UNCLASSIFIED

AD NUMBER

AD905223

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; 01 DEC 1972. Other requests shall be referred to Navy Fleet Miussile Systems Analysis and Evaluation Group, Corona, CA 91720.

AUTHORITY

FMSAEGA D/N ltr, 19 Jul 1973

THIS PAGE IS UNCLASSIFIED

GIDEP Form 2:12-71

GENERAL REPORT SUMMARY SHEET

1 OF 1

1. ORIGINATOR'S REPORT TITLE	2. PROGRAM OR SYSTEM	3. DATE OF	DAY	MO	YR
Steerable Parachutes	MULTIPLE	ISSUE		9	69
	4. ORIGINATOR'S REPORT NO. TP-134	REVISION			

5. ORIGINATOR'S PART NAME/PART IDENTIFICATION	6. REPORT TYPE, ETC.
Parawing T. W. Knacke	Historical and Technical Sep 64

7. THIS TEST (SUPERSEDES) (SUPPLEMENTS) REPORT NO. N/A 29p.

8. MANUFACTURER	9. MANUFACTURER PART NO.	10. MFG TYPE, RATING, SIZE, ETC.
N/A	N/A	N/A

11. OUTLINE, TABLE OF CONTENTS, SUMMARY, OR EQUIVALENT DESCRIPTION

The Parawing, the Parafoil, the Sailwing and the Volplane achieve glide ratios of better than 3 to 1. They are lowering payloads of 6000 pounds from altitudes of 20,000 feet at dynamic pressures up to 100 psf. Their flight characteristics are more representative of gliders than of parachutes. This paper ~~will~~ discusses the historical and technical development, defines aerodynamics stress analysis, deployment characteristics and flight performance, as well as ~~show~~ showing some areas of operational application with emphasis on decoupled landing of logistics shuttle spacecraft.

Per square ft.

Distribution limited to U.S. Gov't. agencies only; Test and Evaluation; 1 DEC 1972. Other requests for this document must be referred to Naval Fleet Missile Systems Analysis & Evaluation Group Code 862, Library Office, Corona, Calif 91720

19 MAY 1972

12. ENVIRONMENTAL EXPOSURE CODES	13. MANUFACTURER NOTIFIED
N/A	N/A

14. KEY WORDS FOR INDEXING

Parawing, Steerable, Glide Ratio, Stress Analysis

15. SIGNATURE	16. PARTICIPANT
(Mrs.) Adrienne Morse, Librarian	Northrop Corporation Ventura Division

17. ACCESS NUMBER D8/53

18. COMPONENT PART NAME PER GENERIC CODE General Technical Data Parts Test and Reliability Mathematics

19. REPORT NO. 347.40.00.00-SE-03

29 001

NOTICES PAGE

FOREIGN NATION RELEASE

This information is furnished upon the condition that it will not be released to another Nation without specific authority of the cognizant agency (Military or NASA) of the United States Government, and that the information be provided substantially the same degree of protection afforded it by the Department of Defense of the United States.

DISCLAIMER OF LIABILITY FROM ACT OF TRANSMITTAL

When Government drawings, specifications or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specification, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Any information disseminated by the Administration Office of the Government-Industry Data Exchange Program (GIDEP) is intended to promote test data utilization in the National interest among groups engaged in the military weapons, aerospace and related programs.

Dissemination of said information does not imply verification or endorsement of the information. The originator, in submitting the material is acting in accordance with the requirements of his contract, and neither the originator nor the disseminator assumes any liability to parties adopting any product, process or practice based upon the usage of the information. Its presenting the success of failure of one (or several) part number(s), model(s), and lot(s) under specific environment and output requirements, does not imply that other products not herein reported on are either inferior or superior.

OMISSION OF CHARGES FOR FOLLOW-ON ACTIONS

Any compliance by the report originator with requests from recipients for more detailed information in GIDEP reports originated under Government contracts will be considered within the scope of present contractual obligations. Compliance with such requests will be at the discretion of the report originator and will be performed without cost or obligation to the requester unless otherwise negotiated in advance.

REPRODUCTION OF THIS REPORT

NORTHROP

TP-134

STEERABLE PARACHUTES

T. W. Knacke

Northrop Corporation
Ventura Division
Newbury Park
California

Paper Presented at the
SYMPOSIUM FOR AERODYNAMIC DECELERATION
Braunschweig, Germany
September 1969

INTRODUCTION

Extensive research and development is being conducted and some operational applications are being investigated on "Steerable Parachutes" or "Lifting Decelerators" as they are frequently called. The third generation lifting decelerators represented by the "Parawing", the "Parafoil", the "Sailwing", and the "Volplane" achieve glide ratios of better than 3 to 1. They are lowering payloads of 6000 pounds from altitudes of 20,000 feet at dynamic pressures up to 100 psf. Their flight characteristics are more representative of gliders than of parachutes. This paper will discuss the historical and technical development, define aerodynamics, stress analysis, deployment characteristics and flight performance and show some areas of operational application with emphasis on decoupled landing of logistics shuttle spacecraft.

HISTORIC DEVELOPMENT

One of the first descriptions of a steerable parachute is found in the November 1874 issue of the American magazine "Scientific American". It shows a picture of the "De Groof Parachute", so-called by the inventor despite the fact that it resembles an early glider concept more than a parachute, see figure 1. DeGroof's idea was to use it as a semi-rigid parachute for escape from balloons. His first jump from a height of 80 feet ended in disaster and may well have discouraged further attempts to develop steerable parachutes.

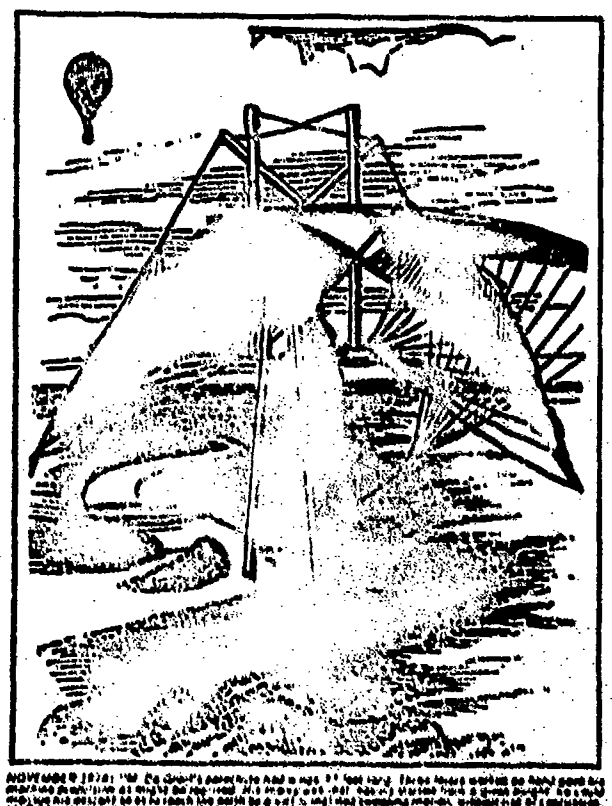


Figure 1 - The DeGroof Steerable Parachute, 1874

That steerable parachutes have occupied inventors in many countries can be seen in figure 2, a caricature of a steerable parachute published with a little descriptive poem in Germany in 1880.

FIRST HE TRIED WITH SKILL AND LUCK
TO HAVE THE CHUTE JUST OPEN UP!
BUT WHEN HE PUT HIS BRAIN IN GEAR,
HE EVEN TAUGHT THE CHUTE TO STEER!

Anfangs fing er mit Genie
nur den Wind im Parapluie.
Später lernte er durch Denken
hin und her den Schirm zu lenken.

Figure 2

It appears that the first gliding parachute was more the result of circumstance than a planned development aimed at designing such a device.

Systematic parachute development did not start u til after WWI. After the introduction of methods for measuring rate of escent it was noticed that gliding parachutes, even if glide was induced by damage, frequently had a lower vertical velocity (rate of descent) than non-gliding parachutes. Jumpers observed that pulling the forward suspension lines and spilling air out the rear of the parachute induced a forward motion, a desirable action since it promoted a forward roll-over-the-shoulder landing. It was furthermore observed that parachutes that suffered damage, such as a ripped gore, would glide.

Without laying claim to historical accuracy, it appears that the Triangular Parachute developed in 1927 by Major Hoffman, then Chief of the U.S. Army Air Service, Parachute Branch at McCook Field, Dayton, Ohio, was the first parachute that glided and could be steered by pulling appropriate suspension lines. This parachute was originally developed as a stable device for lowering airplanes. It had a glide ratio of approximately 0.75 to one. For personnel use it was attached so that jumpers would glide sideways; the intention being that this would make it easier to make an over-the-shoulder roll at landing.

A modified version of the Hoffman parachute was developed as a paratrooper parachute by the German company Henking, and put into limited service by the German Air Force during World War II.

In the late nineteen thirties the Hart and the Deery-Slot steerable parachutes were developed. They employed slots and skirt steps to create thrust by exhausting air to one side of the parachute, thereby gliding in the opposite direction. These parachutes with glide ratios of approximately 0.75 to 1, were used extensively by the smoke jumpers of the U.S. Forest Service in forest fire fighting. They provided a good glide and turn control for landings in wooded and rugged mountainous terrain. The Hoffman Triangular, the Derry, and the Hart parachutes which depended for glide primarily on air exhaust and an opposite reaction force are shown in Figure 3. They are called "first generation gliding parachutes" in this paper. An evaluation of steerable parachutes was conducted by the U.S. Air Force in 1954, Ref. 1. This was probably the first systematic investigation and evaluation of steerable parachutes.

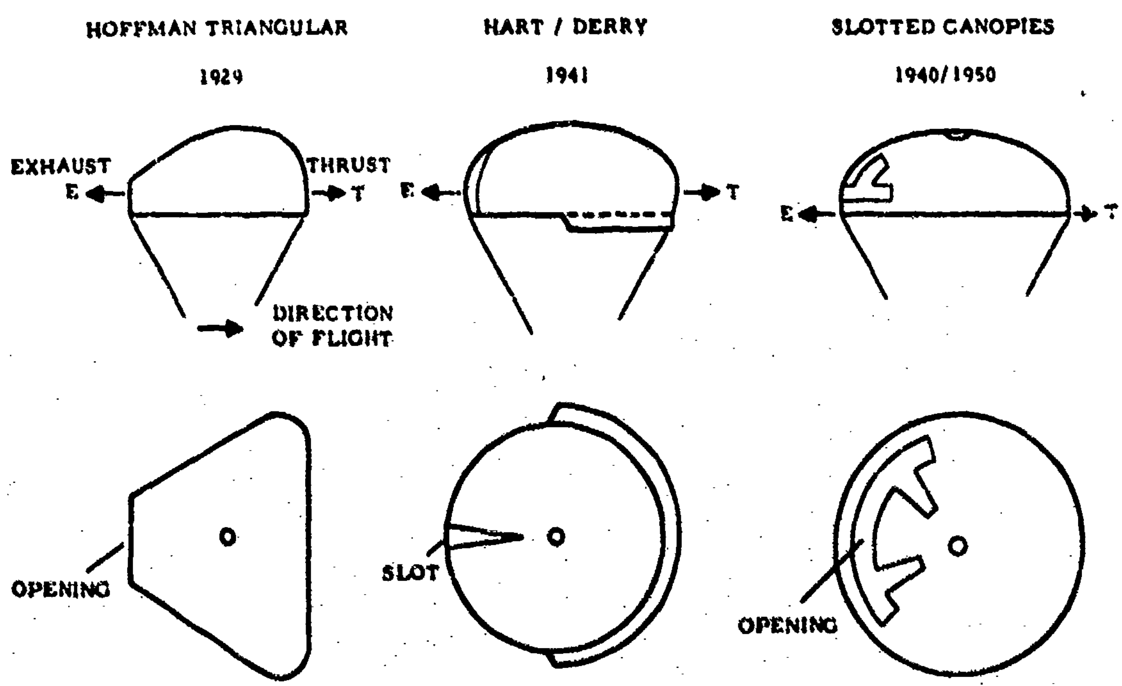


Figure 3 First Generation of Steerable Parachutes

The advancement of lifting decelerators gained a tremendous impetus from two factors, first the need for land landing of spacecraft and second, the interests of sport jumpers and the need for rescue jumpers for parachuting to an exact spot on the ground. Land landing of spacecraft requires the capability to reach pre-selected landing sites in gliding flight, to land in high surface winds, and to avoid ground obstacles on landing. These requirements can be met only by use of a steerable, gliding parachute.

The first real progress toward this goal was achieved by the French Le Moigne parachute, which obtained a glide ratio of better than 1 to 1 and exhibited excellent turn and landing control. The Le Moigne parachute was probably the first parachute with a canopy somewhat in the shape of an airfoil. Numerous attempts were made between 1958 and 1963 to develop parachutes with airfoil type canopy cross-sections. The best known are the Parasail and the Paracommander developed by the Pioneer Parachute Company as modifications of the Le Moigne parachute (3), and the Glidesail and Cloverleaf parachutes developed by the Northrop Corporation (4, 5). The latter, using a good airfoil shape and a high aspect ratio, obtained glide ratios of 1.8 to 1 in free flight. This group of parachutes called the "Second Generation Steerable Parachutes" is shown in Figure 4. All use more or less pronounced airfoil shapes. They depend on air exhaust for adding thrust and forward speed and on wing tip deflection for turn control.

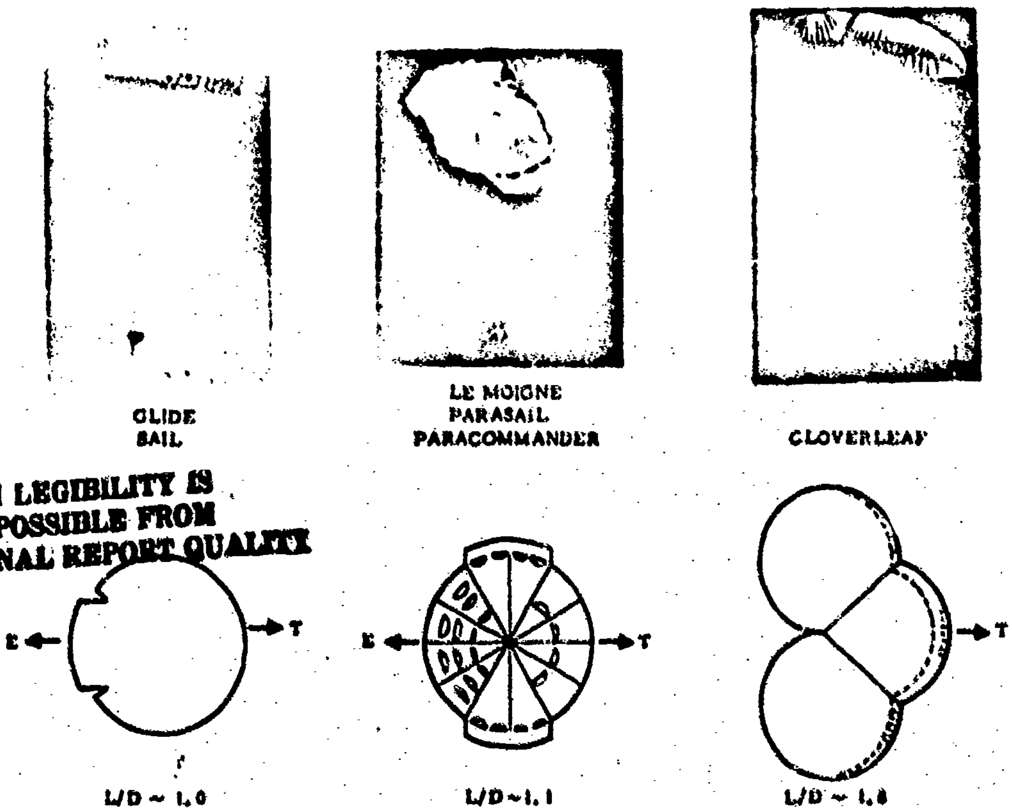


Figure 4 2nd Generation Steerable Parachutes

Real progress was obtained in the third generation of lifting decelerators. This group of parachutes includes the Rogallo Wing (Parawing), the Parafoil, the Sailwing and the Volplane. The Rogallo Wing shown in the twin keel Parawing version in Figure 5 was invented by Francis Rogallo of the NASA Langley Research Center (6). The Parafoil was invented by D. C. Jalbert and developed by the University of Notre Dame (7). David Barish is the inventor of the Sailwing (8). The Volplane is a recent development of the Pioneer Parachute Company and incorporates good features of several other designs.

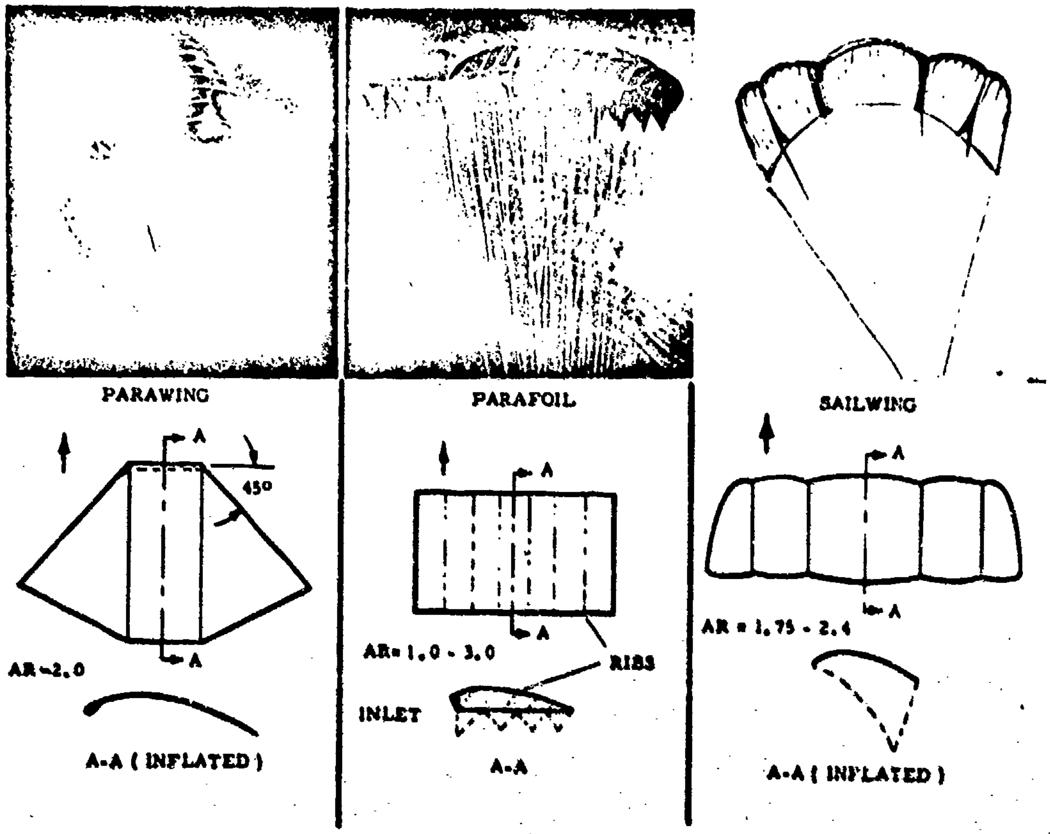


Figure 5 Advance Lifting Decelerators (Third Generation)

There is a close relationship between all four third generation lifting decelerators in aerodynamic characteristics, deployment and opening behavior and flight performance. It should be recognized that these devices resemble deployable gliders that fold, store, and open like parachutes, but fly like airplanes. This characteristic requires extensive development and flight testing which is more similar to that of airplanes than of ballistic parachutes.

AERODYNAMIC CONSIDERATIONS

Parachute tests described in Reference 2 indicated that a solid flat parachute when converting from vertical descent to gliding flight increases its total force coefficient C_R with a resultant decrease in vertical velocity. This phenomemon was not further investigated in 1953, but can be understood by comparing the forces acting on a ballistic parachute and a gliding parachute as shown in Figure 6.

The glide velocity V_T in the direction of flight is:

$$V_T = \sqrt{\frac{2W}{S \cdot \rho}} \cdot \sqrt{\frac{1}{C_R}}$$

With W the vehicle weight, S the lifting decelerator area and ρ the air density, this means that the flight velocity V_T depends, for equal conditions of wing loading and altitude, on the resultant force coefficient C_R. Wind tunnel tests conducted on rigid canopies and open half-shells by NASA, AVA and DVL and summarized in Reference 9 show that the force coefficient C_R will increase with angle of attack. This means if a parachute starts gliding the total velocity will decrease. Since the vertical velocity is $V_V = V_T \cdot \sin\gamma$, with γ the glide angle, it is obvious that a gliding parachute has always a lower vertical velocity in glide than in vertical descent. A parachute with a glide ratio of 3 to 1 will decrease its vertical velocity to 30 percent of that of a non-gliding parachute of equal canopy area. This is one of the great advantages of gliding parachutes since the vertical velocity generally determines the design and the weight of the landing gear or landing impact system. The horizontal velocity and resultant energy can generally be absorbed by low deceleration ground friction devices similar to gliders.

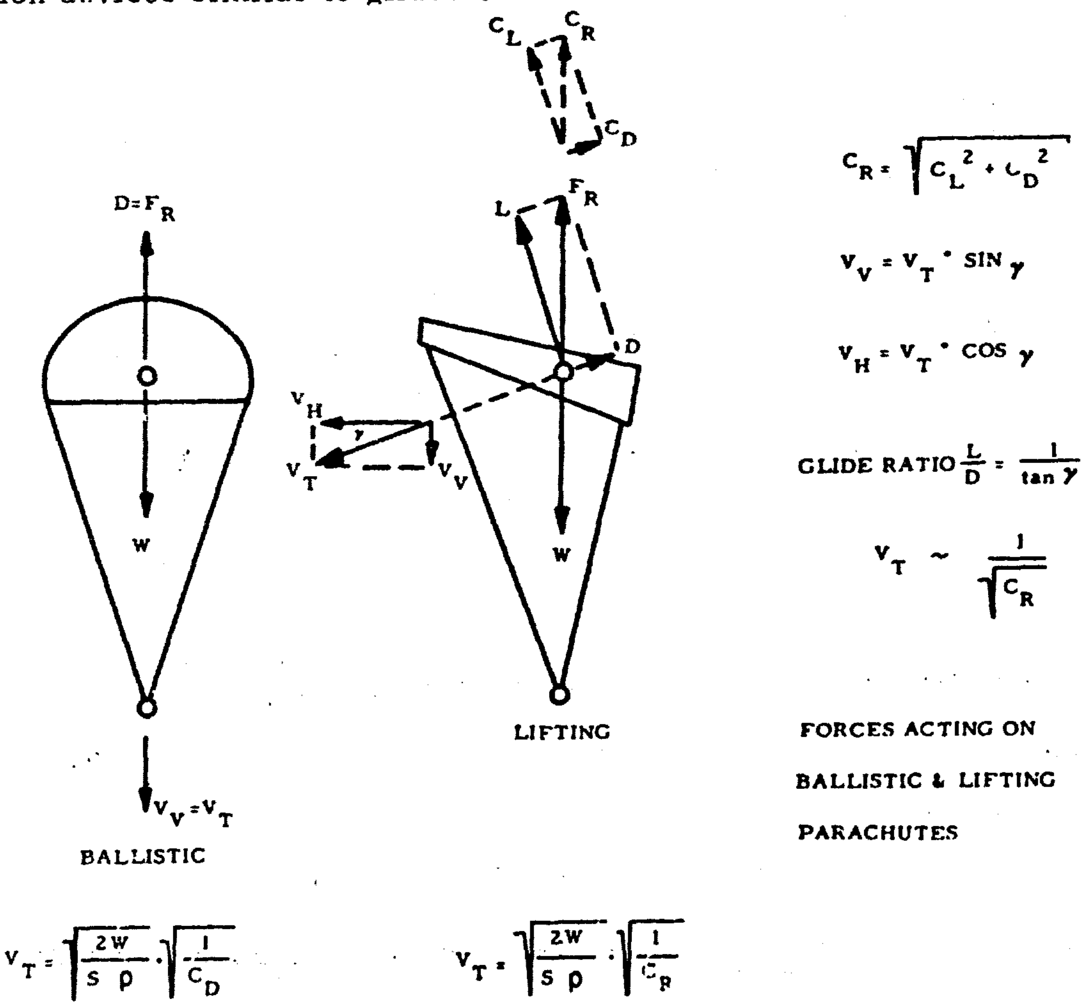


Figure 6 Forces Acting on Ballistic and Lifting Parachutes

Figure 6 also shows the relationship between glide angle, glide ratio and vertical and horizontal velocity.

In order to assess the effect of lift, drag, and velocity on flight performance, it is useful to analyze the lift/drag coefficient diagram in Figure 7. Data measured on rigid canopies from zero to 90-degree angle of attack[9] are compared with data for the Coverleaf parachute and two twin keel Parawing designs of different planforms. The rigid canopy has a moderate increase in resultant force coefficient C_R with increase in angle of attack. Glide angles of more than 30 to 40 degrees cannot be obtained with this type of canopy design due to leading edge cave-in and resultant instability and loss in glide performance. This confirms the test results with conventional standard parachutes in Reference 2 where the glide angle was limited to less than 45 degrees. The Cloverleaf parachute has a L/D modulation range from 1.8 to 0.5. The double flap arrangement in the rear lobes of this parachute makes it possible to reach in a transition stage zero glide and to fly backward.

Some interesting points in analyzing these data are the condition of optimum glide I, the point of maximum flight velocity II, the approximate point of minimum vertical velocity III, and the point of steady minimum glide IV. The lift and drag coefficients plotted in Figure 7 are those of lifting decelerators with the parasite drag of a representative spacecraft vehicle added.

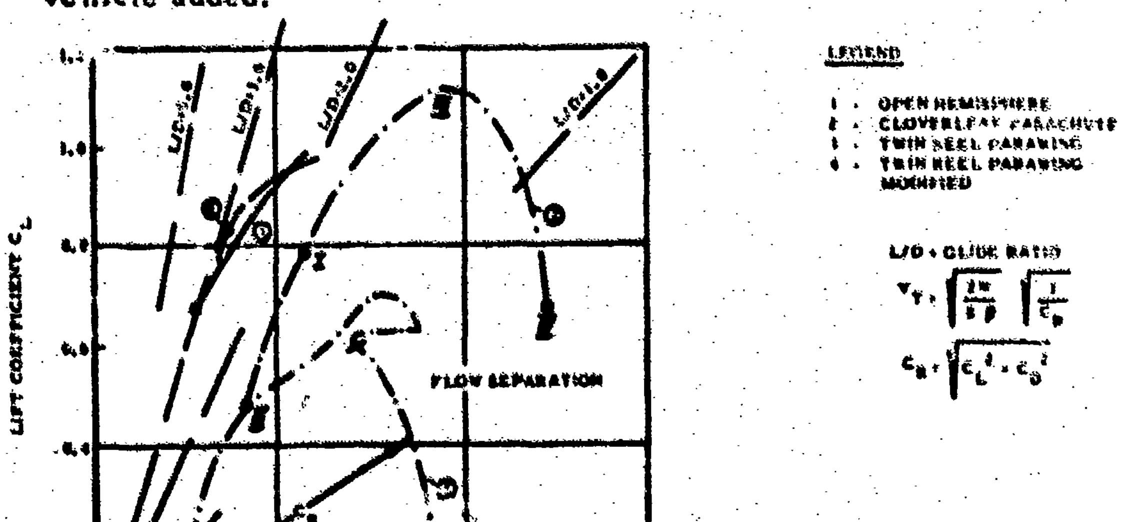


Figure 7 Aerodynamic Characteristics of Lifting Decelerators

A wide variation in glide ratio is desirable for the landing approach since it helps to avoid over-shoot or under-shoot, similar to the effect

of dive brakes on gliders. To use this variation in glide ratio for landing with a slow horizontal velocity is not practical due to the resultant large increase in vertical velocity.

Both twin keel Parawings have a glide ratio of 3 to 1, but only limited L/D modulation which is associated with a Parawing angle of attack range of 25 to 45 degrees. The angle of attack is limited on the low side by collapse of the leading edge and at the high angle of attack by a Dutch-Roll condition and general instability. The Parawing represented by curve 3 is the commonly used planform. The Parawing shown in curve 4 with a modified planform is a recent development and shows certain advantages(6). The point of maximum glide on Parawing 3 is close to the point of leading edge stall whereas on Parawing 4 it is more in the center of the performance range; this Parawing, therefore, is less susceptible to inadvertent leading edge stall. In addition, Parawing 4 has a wider range of maximum glide, a desirable characteristic. The relatively small range of L/D modulation is one of the disadvantages of these high performance lifting decelerators.

An examination of Figure 7 indicates how improvements in future lifting decelerators might be obtained. An increase in lift coefficient seems to be improbable. It appears more practical to strive for a decrease in drag, through increase in aspect ratio, better airfoil shape, decrease in surface roughness, decrease in number of suspension lines, and similar means. Flight performance investigations for several operational applications show the importance of a wide glide velocity range in order to compensate for high surface winds and still permit low speed landings. Normal flight should be possible at a low force coefficient C_R which will produce a high flight velocity. Landings should be made at a high force coefficient C_R, that is, at a low landing speed. These relationships are well understood in glider and aircraft design but are not commonly applied in the analysis and design of lifting decelerators.

Figure 8 shows flight performance, i.e., vertical velocity, horizontal velocity, glide ratio, and effect of wing loading W/S for a ballistic parachute with a glide ration L/D = 0, for the Cloverleaf parachute with a L/D of 1.8, for the twin keel Parawing with a L/D = 3.0, and for a hypothetical lifting decelerator with a L/D of 5.0. The wide velocity and L/D modulation capability of the Cloverleaf parachute results from the large usable C_L/C_D range shown in Figure 7. A very important characteristic demonstrated in Figure 8 is the decrease in vertical velocity with increase in glide ration L/D. A ballistic parachute with a wing loading W/S of 2.0 psf has a vertical velocity of 42 ft/sec. The Cloverleaf parachute with the same wing loading has a vertical velocity of 22 ft/sec, the Parawing 16 ft/sec, and the hypothetical L/D of 5

decelerator 11 ft/sec. This velocity decrease allows the Parawing to obtain a given rate of descent - generally one of the important design parameters - with only 1/7th of the canopy area of a ballistic parachute. This pronounced decrease in surface area is naturally reflected in weight, volume, shorter opening time, etc. For example, a 16 ft/sec rate of descent can be obtained for an Apollo Command Module with a 6500 sq. ft. Parawing, but would require twelve 83.5 diameter parachutes with a total canopy area of 54,000 sq. ft.

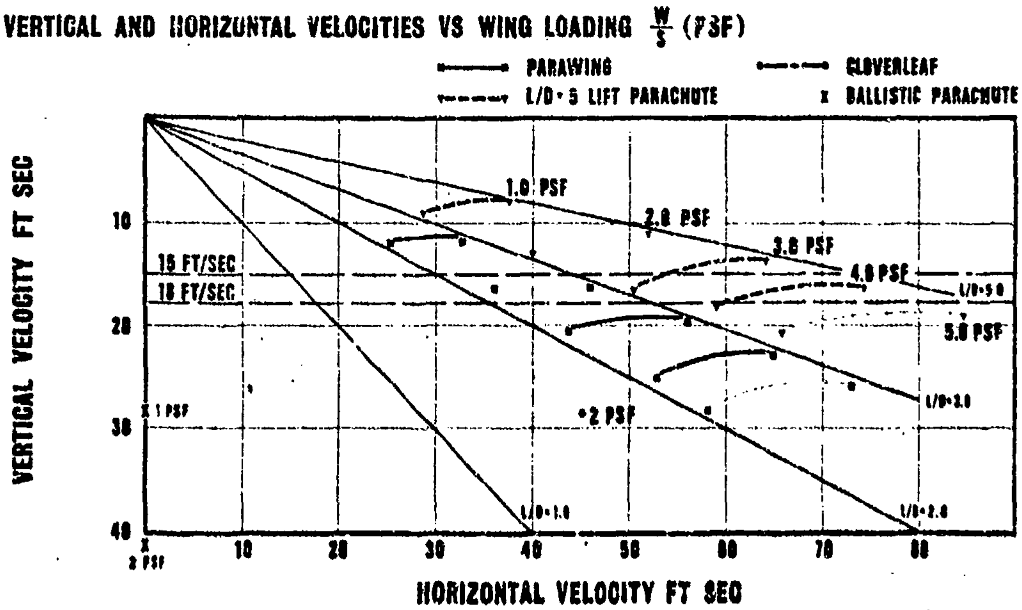


Figure 8 Flight Performance, Vertical and Horizontal Velocity, for Various Wing Loadings, W/S

A glide ratio of 5 to 1 seems to be the upper limit that may be obtainable with an all flexib'e lifting decelerator. This is based on the following considerations: A 4824 NASA airfoil with an aspect ratio of 2.0, rounded trailing edge, wrinkled surface, and the parasite drag of suspension lines and payload added will reach a glide ratio of approximately 5. It should be possible to reach this glide ratio of 5 to 1 with

012

advanced lifting decelerators. Figure 9 shows the historical development in glide performance and L/D modulation range as well as the projected future increase.

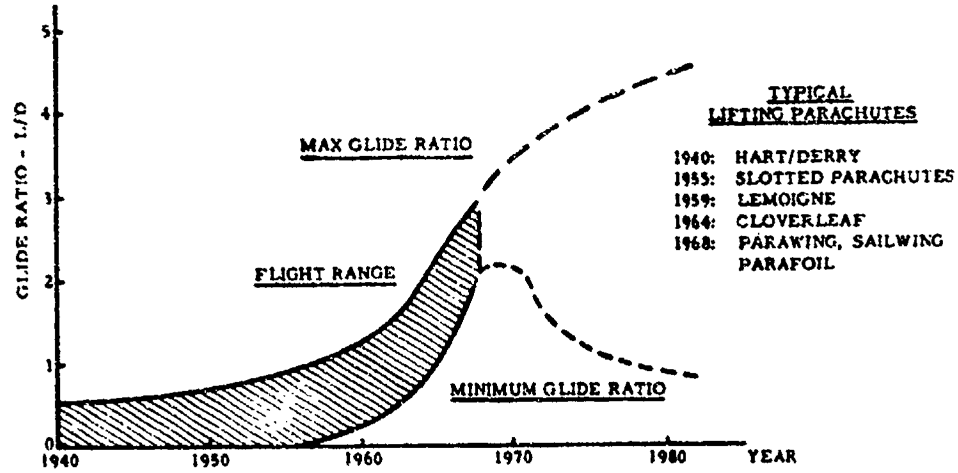
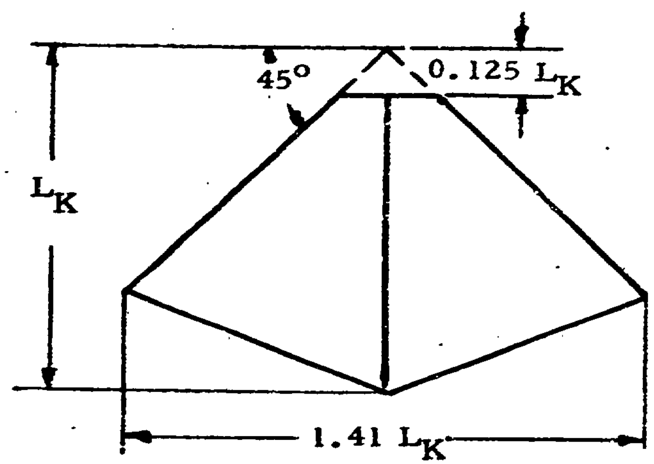


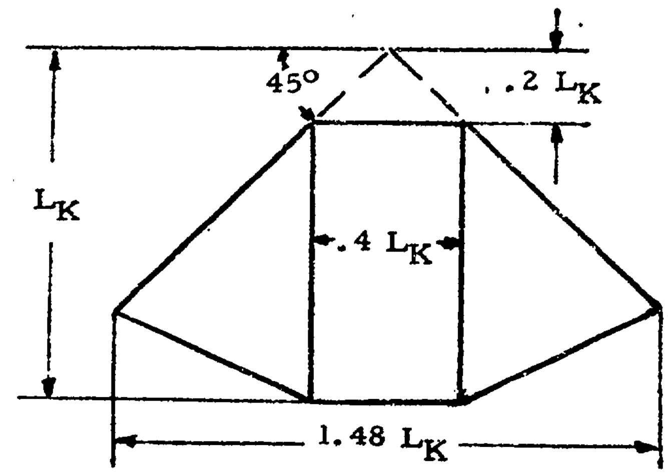
Figure 9 Past, Present and Predicted Future Performance of Lifting Parachutes

PARAWING DEVELOPMENT

Of the four advanced lifting decelerators, the Parawing in its twin keel, single keel, and slotted single keel version has been most extensively investigated, primarily for spacecraft landing, precision aerial delivery, and personnel parachute applications. The Ventura Division of the Northrop Corporation in 1967 obtained from the NASA, Langley Research Center a development contract for investigation of single and twin keel Parawings for logistics spacecraft application. The goal of this development was to establish the technology for a Parawing suitable for landing of a 15,000-pound spacecraft. Requirements included a glide ratio of better than 2 to 1, a vertical touch down velocity of not more than 15 ft/sec, and a maximum Parawing opening force to payload weight ratio of not more than 3 g's.

Figure 10 shows a 400-sq. ft. single keel and a 4000 sq. ft. twin keel Parawing in flight with vehicles of 400 pounds and 6000 pounds. Table 1 lists the various development phases, the wing dimensions, weights, and glide and turn performance obtained in tests. Wind tunnel tests, small scale, and medium scale tests are completed. The tests covered a wing loading range of 1.0 to 1.5 for the small and medium scale tests using a high drag test vehicle. Flight performance was measured with on-board and range instrumentation. A total of 30 uncontrolled flight tests were conducted for investigation of opening characteristics and loads and 27 flights were made with instrumented ground controlled vehicles





	Wind Tunnel		Small Scale		Medium Scale		Full Scale
	Single	Twin	Single	Twin	Single	Twin	Twin (2)
Vehicle Weight, Pounds	-	-	400	600	4000	6000	15,000
Wing Area, Sq Ft	150		400		4000		10,000
Wing Span, Ft	21.1	21.8	33.8	34.8	107.3	110.1	173.8
Keel Length, Ft	14.7	13.9	24.1	22.8	76	72	113.8
Wing Weight, Pounds	-	-	23.8	31.7	295	314	916 (3)
Glide Ratio L/D	2.6	3.4	2.4	3.0	(1)	2.8-3.6	

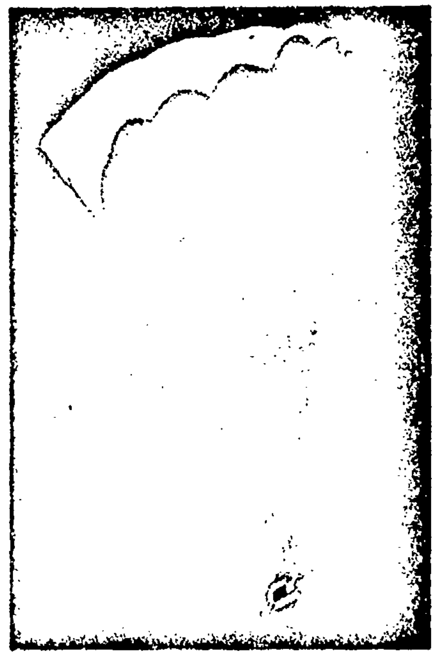
(1) Not measured (2) Not tested (3) Estimated

Table 1 Investigated Parawing Types

014

for determination of flight performance [10].

TWIN KEEL PARAWING



SINGLE KEEL PARAWING

Figure 10   Parawing Types

Flight tests of Parawings are quite similar to aircraft flight tests in the amount of data recorded and in the general flight tests approach. The twin keel Parawing, besides having a notably better glide ratio, demonstrated good stability in pitch, roll and yaw. The single keel wing was less directionally stable in uncontrolled flight, but could easily be flown in controlled flight. Variations in textile materials and fabrication tolerances preclude a symmetrical Parawing. This results in a slight built-in turn rate, on the order of 1 to 5 degrees/sec, making a trim adjustment of the turn control desirable. It was also found practical to introduce a pitch control capability similar to airplanes. This prevents flying too close to a condition of leading edge stall and provides for recovery from inadvertent stall due to wind gusts. Leading as well as trailing edge stalls are good natured. They result in an increase in descent rate, but recovery is automatic. Once adjusted, the Parawings will maintain stable flight.

Turn control is obtained by deflection of the wing tips and/or the keel lines in the twin keel version. Turn rates up to 100 degrees/sec were flown with the 400 sq. ft. wing and rates in excess of 25 degrees/sec were flown with the 4000 sq. ft. Parawing. Investigations by NASA Langley, NASA MSC, and by Northrop indicate that turn rates of 6 to 8 deg/sec are entirely satisfactory for controlled manned flight and automatic beacon flights (11). Larger turn rates result in oversteer and undesirable high control system power requirements.

Limiting opening loads to a 3 g level caused the greatest problem and necessitated extensive development. The severity of this requirement is clear if one relates this to other parachutes. A personnel parachute, when opened at a dynamic pressure of 100 psf at 18,000 feet altitude, has an equivalent g-loading of 15 to 20 g's. Tests with several lifting decelerators including Cloverleaf and Parawing indicate that for infinite load conditions the opening time is about half that of a standard solid material parachute of equal wing area and the dynamic load factor $C_K = \frac{F_o}{C_D \cdot S \cdot q}$, is in the range of 2.5 to 3, almost twice as high as for a conventional parachute. This high opening load factor is typical for all lifting decelerators that are fabricated from coated textile materials with close to zero porosity.

Reefing, a well established technology for parachutes, was used as the primary means for obtaining a 3 g load limit. It was found practical to maintain all suspension lines at equal lengths during deployment in order to avoid premature gliding. Glide during the opening phase causes sail-type indentations and interferes with proper, progressive, sequential opening. One may paraphrase the technical approach used as "Deploy like a parachute and fly like an airplane." The resulting successful reefing sequence is shown in Figure 11 for a twin keel Parawing. All three Parawing lobes, as well as the two trailing edges, are reefed with individual reefing lines. The first stage inflation is similar to a balloon inflation, relatively slow and steady. The two outer lobes, then the center lobe and finally the nose and trailing edges are disreefed in successive steps. The final step is the release of the suspension lines to the flying position. This five stage reefing process reduces the maximum loads to a level of 3.5 g's.

It was not possible to reach the desired 3 g level. Opening in the successive reefing stages is fast and positive. The problem is not slow opening, but rather too fast an opening, caused by the low porosity cloth. In over two hundred flight tests with Parawing and Cloverleaf steerable parachutes, Northrop has never had an opening failure for aerodynamic reasons, or lost a test vehicle due to destruction of the decelerator.

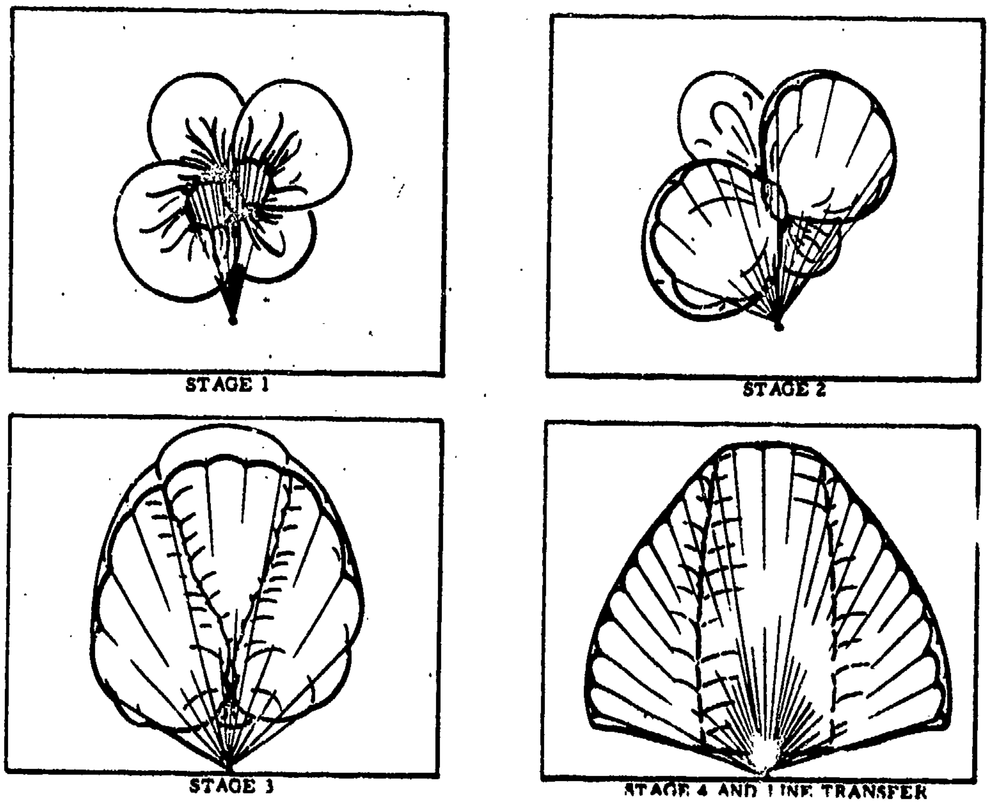


Figure 11. Twin Keel Parawing Reefing Stages

A typical opening force diagram for a 4000 sq. ft. wing opened at a dynamic pressure of 24 psf at 19,000 ft. altitude with a 3500 pound vehicle is shown in Figure 12. It clearly demonstrates the slow balloon-type opening of the first stage and the rapid opening of all successive stages. Deployment at higher dynamic pressures affects primarily the first stage load, but has little effect on the consecutive stages.

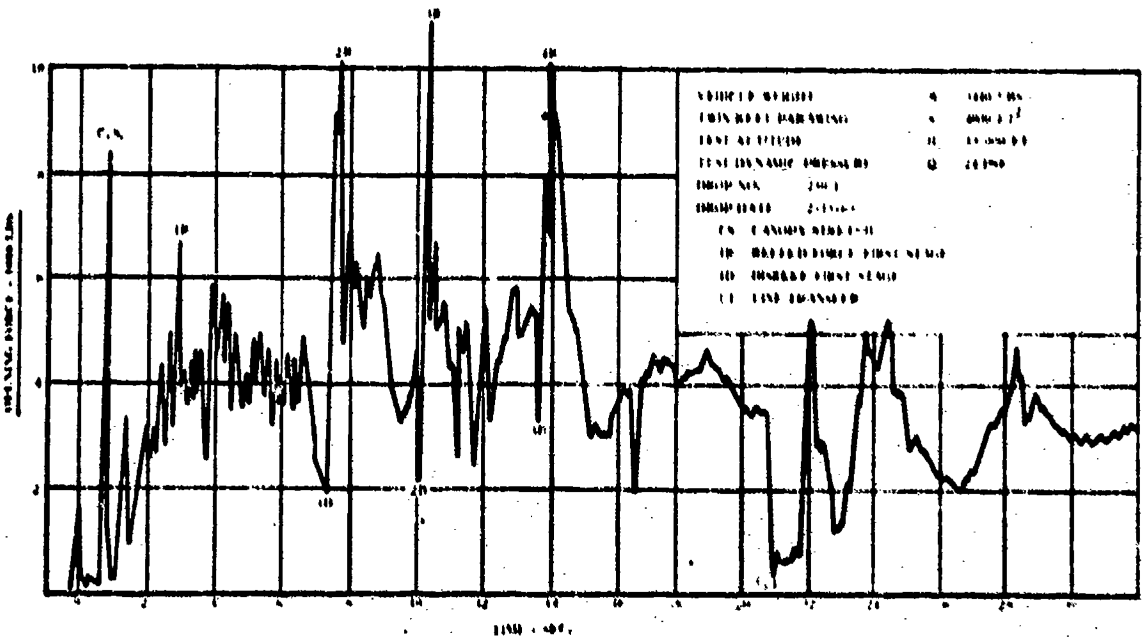


Figure 12 Twin Keel Parawing-Opening Force/Time Diagram

017

No precise solution is available for predicting load and stress distribution in parachute canopies during opening. This is even more complex for unsymmetrical Parawings. Using analogies to pressure distribution measurements in canopies, Northrop has developed load and stress approximations that gave good agreement with measured loads. No test resulted in destruction of a Parawing.

SPACECRAFT LANDING WITH LIFTING DECELERATORS

A spacecraft landing concept is demonstrated in Figure 13. Future logistics shuttle spacecraft will use land landing as the primary mode of return, but will maintain a backup water landing capability. The total process is rather similar to aircraft or glider landing in its descent, approach, and landing phases. Normal landing will occur on a prepared landing site; most likely an airport. The zero-lift trajectory for the final landing phase will be known. The de-orbit point will be offset for wind drift and meteorological conditions. De-orbit, reentry, and descent prior to parawing deployment will permit, with advanced guidance and navigation (G & N) concepts, a 6 mile diameter Parawing deployment window. The window may extend to 10 miles in diameter with a less sophisticated G & N concept. This includes deployment of a drogue chute at 40,000 to 50,000 feet for initial ballistic deceleration. Ground communications, on-board instrumentation, and ground controlled instrument landings will allow all weather landings in an area of about 5000 feet in diameter.

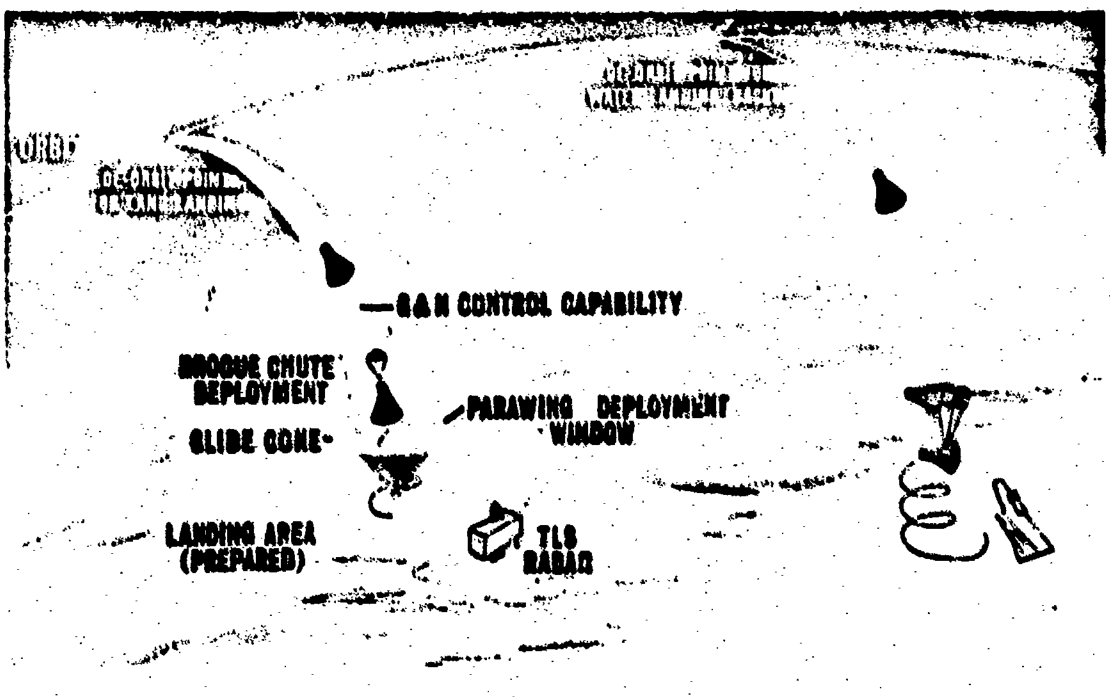


Figure 13 Spacecraft Land Landing Concept

A lifting decelerator spacecraft land landing system must meet the following requirements:

Capability to reach a pre-selected, prepared landing area in gliding flight.

Forward landing capability in ground winds up to 35 knots.

Low vertical touch down velocity.

Avoidance of ground obstacles.

Capability to land on land and water.

Capability to reach a suitable landing site in emergencies.

A study recently conducted by Northrop for McDonnell Douglas and NASA for a logistics spacecraft land landing system capable of transporting cargo and 12 men to and from an orbital space station resulted in the following system:

<u>Requirements</u>

Vehicle weight = 18,000 pounds.

Vertical touch down velocity = 18 ft/sec.,

Landing requirements as outlined previously.

<u>Study Results</u>

Twin keel parawing with four steps of reefing,

Wing Load W/S = 2.25 psf.,

Wing Area = 8000 sq. ft.,

Turn Rate = 6 to 8^{o}/sec.,

Pitch-trim and roll control,

Duplicate Parawing backup system,

Max load during opening = 62,000 pounds.

The wing loading of 2.25 psf is somewhat conservative as can be seen from Figure 8 and as demonstrated in medium scale Parawing tests. The weight of the 8000 sq. ft. Parawing assembly is approximately 760 pounds. The total system weight including double drogue chute assemblies, control systems, Parawing backup system, and installation is estimated at 1790 pounds, not including landing gear. This study defined the importance of static and dynamic stability of the Parawing spacecraft system with small control forces and a small control system duty cycle for saving battery weight. Investigations of several backup systems including ballistic parachutes with retro rockets, either did not meet the landing requirements or resulted in more extensive development and test programs and, accordingly, higher development cost.

The final system is shown in Figure 14. The wing span for the flat Parawing of 152 feet contracts in flight to 84 feet. The pitch trim lines are visible in the right picture and the wing tip roll control lines in the left picture. All components of the landing system, the dual drogue chutes, dual Parawings, and dual controls are housed in a compartment on the upper side and the landing gear in a compartment on the under side of the spacecraft.

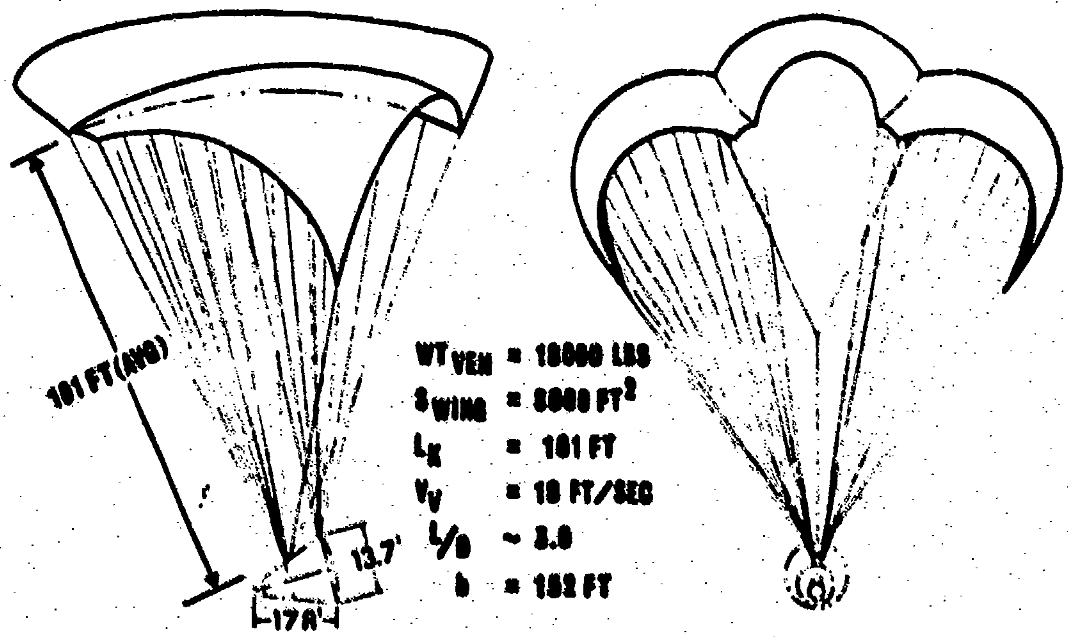


Figure 14 Logistics Spacecraft with Parawing, W/C = 2.25 PSF

THRUST AUGMENTED LANDING CONCEPT

The use of rocket thrust for final landing retardation has been extensively studied and experimentally proven by the NASA Manned Spacecraft Center in Houston for a Gemini-Parasail land landing concept(11).

These investigations were conducted with short time, high "g" vertical thrust applied immediately prior to touch down. Recently, low, long duration, horizontal and vertical thrust augmentation has been investigated and found to offer notable advantages. Figure 15 shows the investigated concepts. The left figure demonstrates the normal landing without thrust requiring a wing loading of 2.25 psf for a vertical touchdown velocity of not more than 18 ft/sec. The center figure shows long duration, low vertical thrust; this acts like a decrease in wing loading. The right figure demonstrates a long duration, low horizontal thrust concept. This acts like a reduction in vehicle drag, results in a better glide ratio and therefore in a reduction in vertical touchdown velocity. Both approaches allow the use of high wing loading parawings resulting in higher flight velocities. The excess vertical velocity is decreased prior to touchdown by the application of rocket thrust to the allowable value of less than 18 ft/sec.

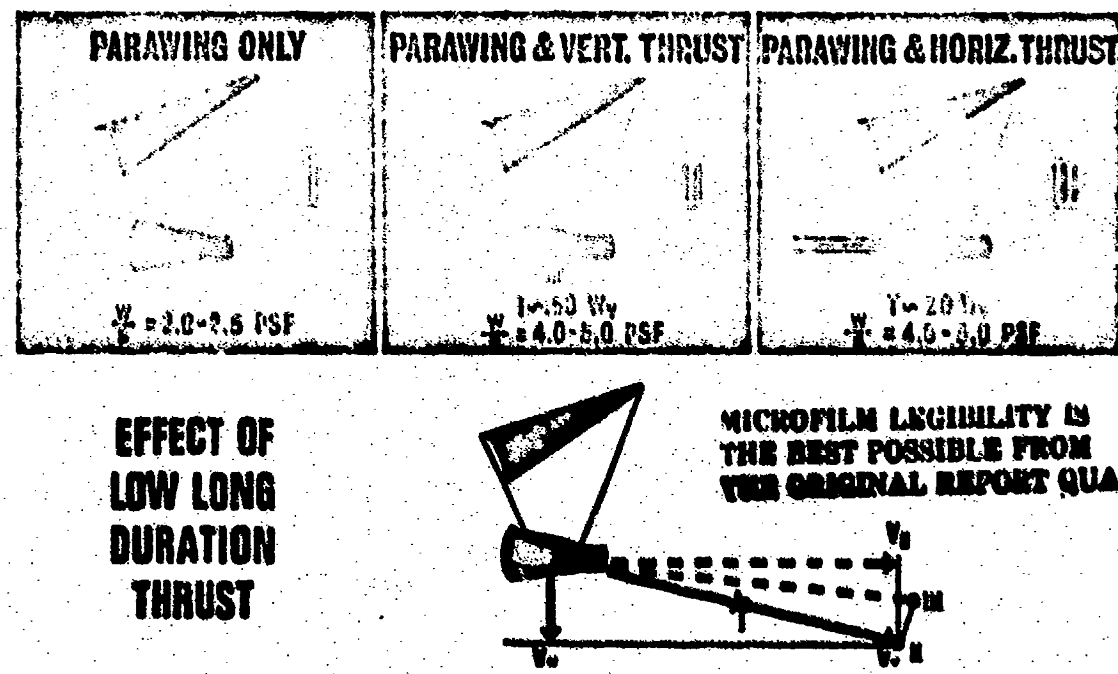


Figure 15. Lifting Parachute Landing Concepts.

Flying with higher wing loading means a smaller, lighter, and less bulky wing. It also achieves better wind penetration and better control response with higher flying speeds and, in case of a pad abort, a reduction in required launch escape system altitude due to the faster opening time of the smaller Parawing. A ten second horizontal thrust augmentation at a thrust to weight ratio T/W of 0.2 is a good solution with regard to weight optimization. Applying horizontal thrust causes practically no change in horizontal velocity since this velocity is determined by the lift coefficient which does not change.

The decrease in touch down velocity for various thrust ratios T/W and various wing loadings W/S can be seen in Figure 16.

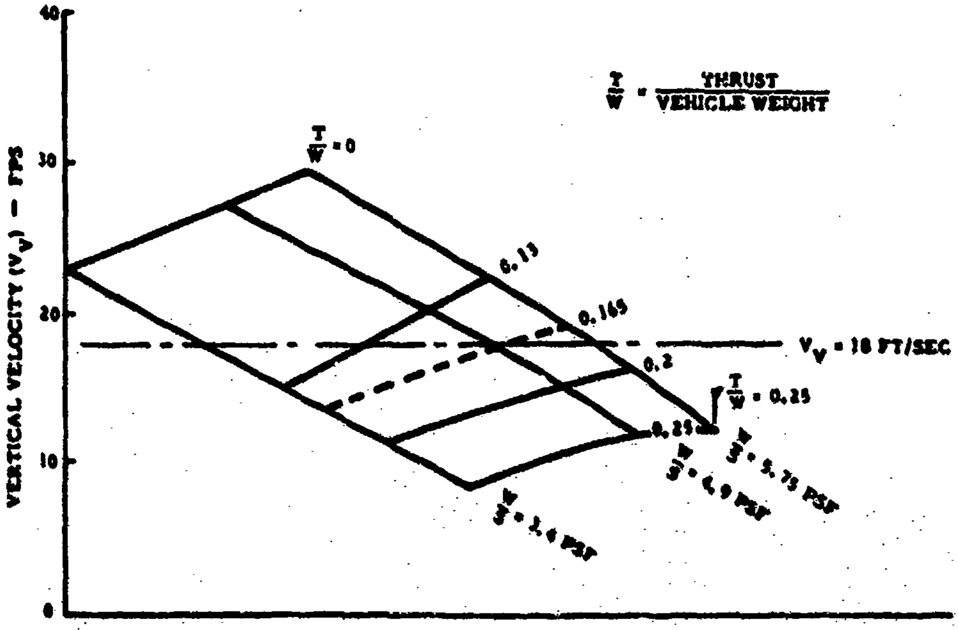


Figure 16 Decrease of Vertical Velocity Due to Thrust Augmentation.

For a wing loading of 4.9 psf, a T/W of 0.17 is satisfactory to reduce the vertical velocity from 26 ft/sec to 18 ft/sec. The duration of thrust augmentation is determined by the time required for the Parawing/spacecraft system to re-stabilize longitudinally after start of thrust augmentation. Incremental application of thrust with a cluster of small rockets is advantageous for stability and for reliability reasons. A thrust time of 10 seconds is a practical value. The landing system weight saving which can be realized by use of horizontal thrust augmentation was determined to be approximately 200 pounds for a total system weight of 1790 pounds. This concept has not been tested so far, but appears very attractive for reasons mentioned before.

DESCENT AND LANDING CONCEPT

A typical descent, approach, and landing procedure is shown in Figure 17.

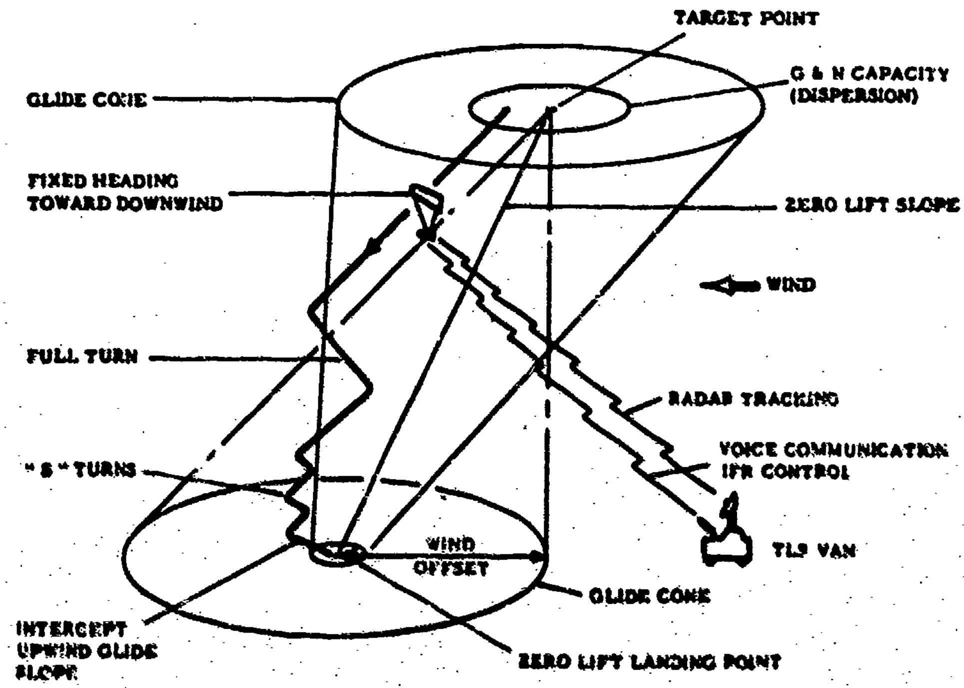


Figure 17. Spacecraft Descent and Landing.

This method discussed in the following paragraphs has been investigated by the NASA Manned Spacecraft Center and the NASA Langley Research Center.* The point of retro-fire for start of de-orbit includes compensation for wind and meteorological condition during the Parawing descent and landing phase. Parawing opening occurs within the Guidance and Navigation (G&N) dispersion window, a circle with radius of a predictable maximum error. The glide cone of the lifting decelerator is defined by a circle approximately three times the diameter of the G&N dispersion window at 20,000 feet altitude. The spacecraft pilot lands either with visual flight control checked by radar tracking and voice communication, or with IFR procedures. Experience has shown it to be practical to fly toward the down-wind side of the landing area, fly a full circle around the area, and to descend in S-turns on the down-wind side; then to pick up the glide slope and localizer and make a normal landing. The visibility from the spacecraft is, most likely, quite limited if compared to standard aircraft. It is, therefore, important to have landing field and final landing markers displayed for orientation similar to the procedure used for landing of the X-15 and HL-10 research aircrafts.

* Both NASA centers have contributed unpublished information for the discussion of the descent and landing concept.

Instrument landing can be performed using normal aircraft automatic flight control procedures. NASA personnel who have gained experience in actual and simulated Parawing-spacecraft landings, point out the similarity to normal aircraft landings using IFR procedures.

A typical spacecraft/Parawing descent with thrust augmented landing is shown in Figure 18.

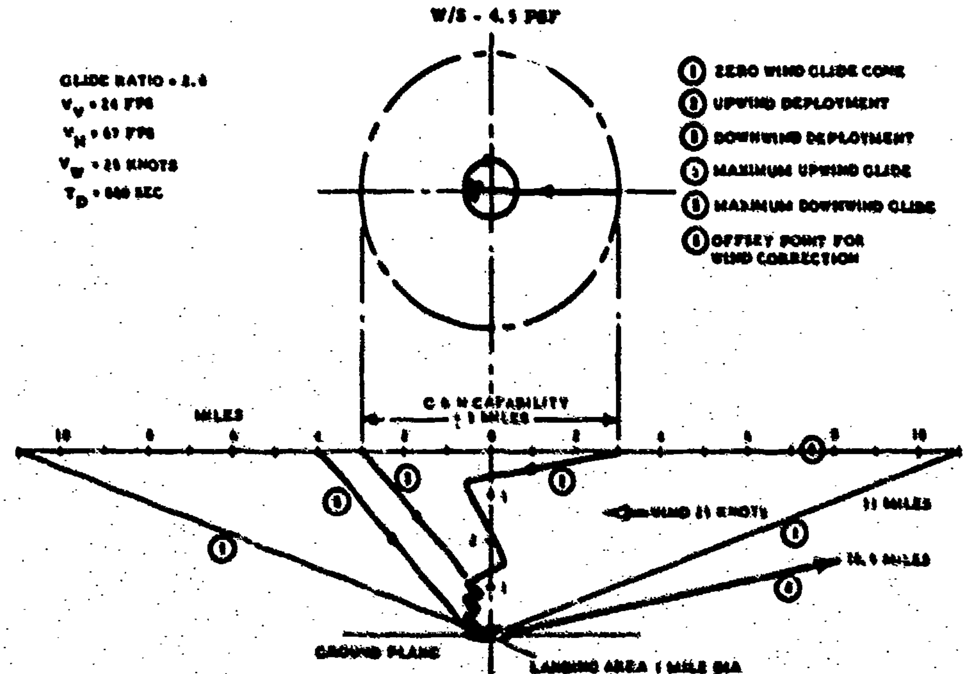


Figure 18 Typical Spacecraft Descent and Landing Pattern, W/S = 4.5 PSF.

If Parawing deployment occurs at 4 miles altitude, a zero-wind glide capability of 11 miles exists. If it is assumed that a 25-knot constant ground wind exists and that no wind compensation was included in the deorbit point, the glide range changes to 13.5 miles if deployment occurs upwind from the landing point and to 4 miles for downwind deployment. This means that even if the S/C ends up on the downwind side of the G&N cone, it could still reach the preselected landing area. Should the S/C find itself on the upwind side of the Parawing deployment window, it would glide to the downwind side of the landing area. The pilot could make a full circle around the landing area to familiarize himself with the landing field and then make his S-turn final descent. An S-turn descent compared with a spiral descent has the advantage that the resultant velocity vector always has the nose of the S/C pointing toward the landing area. The pilot, therefore, has the landing site in view most of the time. All pilots who have flown simulated landings stress the need for visibility and orientation during final landing.

As already mentioned, this discussion of spacecraft/Parawing landing refers to a system using thrust augmentation for final landing. Its high wing loading and resultant high velocity gives a good wind penetration capability. Landing without thrust for this condition of 25 knots wind and no wind compensation results in a marginal capability for reaching the landing area if deployment of the Parawing occurs on the downwind site of the G&N capability cone. Wind compensation or multiple adjacent landing areas are required for this case.

LANDING ACCURACY

NASA Langley has conducted numerous landings with ground controlled small spacecraft type vehicles. Subsequently several hundred simulated landings were made using a photographic landing area display, an optical tracker slaved to pilot control, and a real time computer. The results of approximately 500 landings are shown in Figure 19.

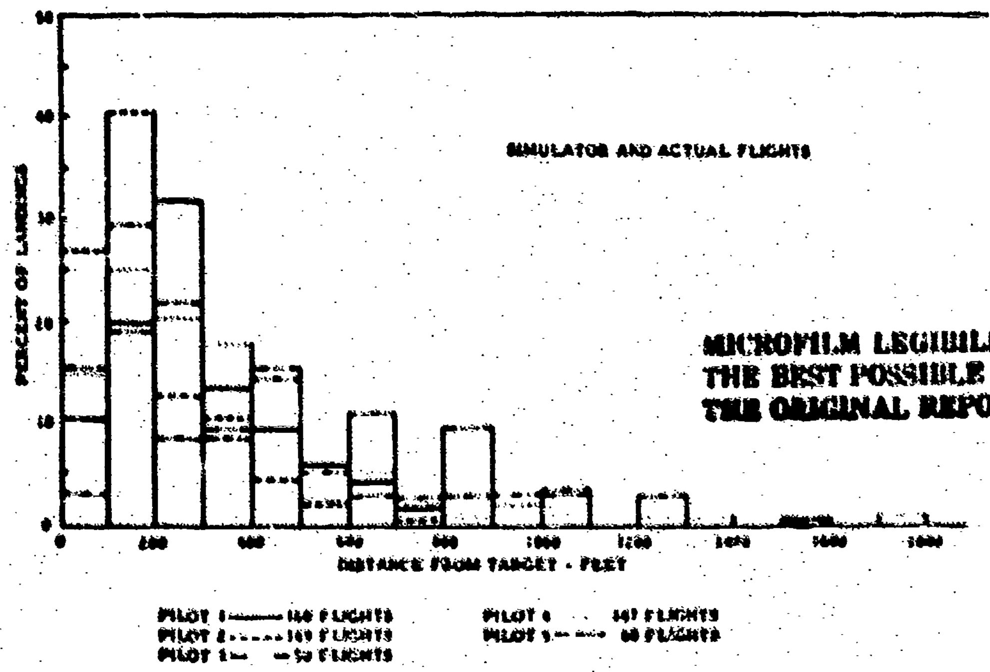


Figure 19 Landing Accuracy.

Of the five operators, three were engineers and two were experienced pilots. Flights were conducted with and without ground winds, with each operator starting the descent at 20,000 foot altitude positioned in various points of the Parawing glide cone. The operator in most flights, but not in all, had a knowledge of the local winds. The results are remarkably good. Operators who find themselves at 20,000 feet altitude, within the glide capability of the system relative to the landing area can land within a 3000 foot diameter circle with or without knowledge of the local winds. Operators had a training of 5 simulated flights prior to this test series. Reasonable visibility or ground guidance and markers were provided for final orientation and landing help.

It is frequently overlooked that the landing rolls after touchdown at these velocities are very short if special high friction skids are used. Figure 20 gives landing roll as a function of touchdown velocity and surface condition. Landing rolls of 50 to 200 feet will result from all but the most extreme landing velocities and ground conditions.

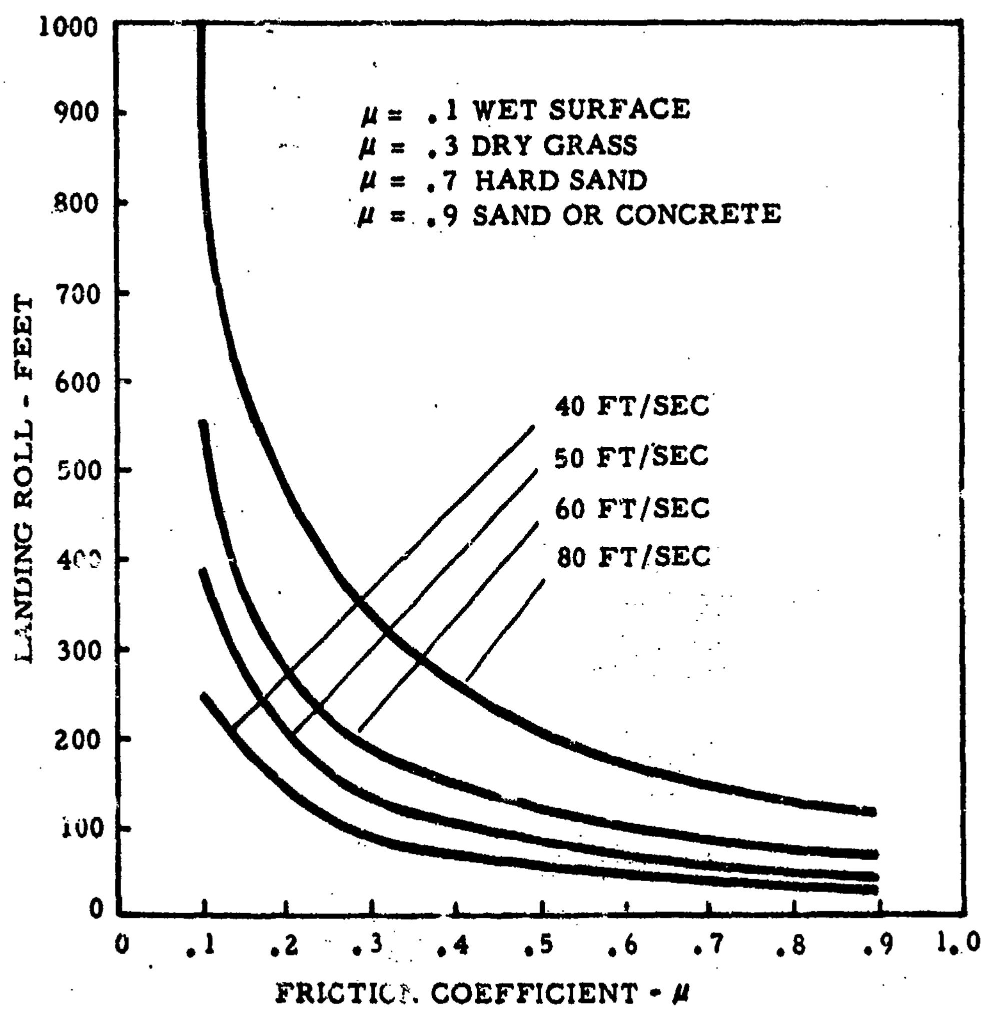


Figure 20 Spacecraft Landing Roll After Parawing Landing for Various Touchdown Velocities.

CREW STATION AND GROUND FACILITY REQUIREMENTS

Tests and studies conducted so far for various types of spacecraft suggest following displays, pilot controls, and visibility requirements:

Pilot Displays

Heading
Altitude
Sink rate
Turn line position
Trim line position
Direct viewing capability or TV camera or optical periscope type device

Pilot Controls

Drogue chute deployment
Parawing deployment
Back-up system deployment
Field of view scanning
Turn (roll) control
Pitch trim control
Augmented thrust control

Ground facilities of any operational airport will meet most landing requirements, including tracking radar, glide slope, localizer, and meteorological data. It should be backed up by a mobile special terminal landing system unit as developed by NASA MSC containing tracking radar, voice communication and ILS landing control provisions. Specialized ground handling equipment should include retrieval vehicle, preliminary spacecraft storage and inspection facility and special bio-medical facilities, if required.

A 5000 foot diameter main landing field is desirable. Nearby emergency landing areas may be required if a low wing loading, low speed configuration is selected with limited wind penetration capability. The landing field should be clear of obstacles such as rocks and trees, it may have a surface of sand, concrete or grass. The inclination should be not more than 1°, equivalent to a 1:60 slope. These requirements are met by hundreds of aircraft landing fields in the United States and other parts of the world.

Emergency landings are similar to glider landings. In fact, the more intensive the investigation of landings becomes, the simpler the landing appears and quite related to normal glider landings.

DEVELOPMENT STATUS

There is little doubt that given the go-ahead, a spacecraft Parawing land landing system can be developed for vehicle weights exceeding 25,000 pounds. Aerial delivery equipment weighing 50,000 pounds is already being recovered by parachute. The step from a 6000 pound test vehicle which is flying with excellent performance, to an 18,000 or 25,000 pound vehicle is less complex that the step from the 500 pound vehicle tested in 1968 to today's 6000 pound vehicle. There will be the normal development problems associated with any increase in size, but the technology to develop such a system exists today.

[redacted]

REFERENCES

1. Rosenberg, Isador and David Gold, "Steerable Parachutes," USAF Report FTL-55-1.

2. Knacke, Theodore and Alfons Hegele, "Model Parachutes, Comparison Tests of Various Types," USAF Report MSREXE-672-12B.

3. Nichols, C.W., "Performance Evaluation of Paracommander Mark I Personnel Parachute," USAF Report FTL-66-16.

4. Riley, V.F. and Carl R. Graham, "Glidesail Development Program," Northrop Corporation, Ventura Division Report PTM-524A.

5. Linhart, E.M., V. F. Riley and C. R. Graham, "Investigation of Various Textile Parachutes and Control Systems to Achieve Steerability," USAF Report FLD-TDR-64-81, Part I to III.

6. Sleeman, William C. and Thomas G. Gainer, "Status of Research on Parawing Lifting Decelerators," Proceedings of 1968 Aerodynamic Deceleration Systems Conference, AIAA Paper 68-967 and USAF Report FTC-TR-69-11.

7. Nicolaides, D.J., R. S. Speelman III and G. L. C. Menard, "A Review of Parafoil Progress," Proceedings of 1968 Aerodynamic Deceleration Systems Conference, USAF Report FTC-TR-69-11.

8. Ware, G.M. and C. E. Libby, "Wind Tunnel Investigation of the Static Aerodynamic Characteristics of a Multilobe Gliding Parachute," NASA TN D-4672.

9. Hoerner, S.F., "Aerodynamic Drag," page 141, 1951 Edition.

10. Linhart, E.M. and W. C. Buhler, "Wind Tunnel and Free-Flight Investigations of All-Flexible Parawings at Small Scale," Northrop Report NVR-6366A.

11. Norman, L.C., S. E. McCullog and S.C. Coffey, "Gemini Land Landing System," Part I and II, NASA TN D-4672.

029